

21. Multipurpose Electric Furnace

Experiment MA-010

A. Boese,^{a†} J. McHugh,^b and R. Seidensticker^b

ABSTRACT

Experiments on solidification, crystal growth, and other processes involving phase changes in various type materials were performed in the multipurpose electric furnace developed for the Apollo-Soyuz Test Project. Phase changes were conducted at elevated temperatures (as high as 1423 K (1150° C)) in systems comprising selected combinations of solid, liquid, and vapor phases. Because of the near-zero-g environment aboard the spacecraft, the liquid and vapor phases were essentially quiescent, and phases of different density had little or no tendency to separate.

INTRODUCTION

The Multipurpose Electric Furnace Experiment facility for the Apollo-Soyuz Test Project (ASTP) was based on a similar furnace (denoted M-518) that was operated onboard the Skylab. The furnace was used to heat and cool material samples in space and thereby take advantage of the lack of thermal convection and sedimentation during the liquid or gaseous phase of the material. Seven experiments in solidification and crystal growth from vapor or melts were performed: Surface-Tension-Induced Convection (MA-041),

Monotectic and Syntectic Alloys (MA-044), Interface Markings in Crystals (MA-060), Zero-g Processing of Magnets (MA-070), Crystal Growth From the Vapor Phase (MA-085), Halide Eutectic Growth (MA-131), and Multiple Materials Melting (MA-150). These experiments are described in sections 22 to 29, respectively.

The motivating concept for the MA-010 experiment was that, at the present stage of the space-processing program, there are many useful preliminary space experiments that can be performed simply by applying prescribed heating and cooling programs and/or known temperature distributions to selected experimental samples of materials. For example, the simple process of growing a Bridgman crystal of a pure metal by directional solidification becomes an interesting new experiment in space because convective heat and mass transport will be largely suppressed in the melt. Many other similar examples exist.

The guiding design requirement for the multipurpose electric furnace system was to produce an apparatus that provided the widest possible flexibility in applying predetermined temperature distributions and temperature/time sequences within the constraints imposed by existing interfaces. Although the Skylab multipurpose furnace met all expectations of performance and reliability, it was apparent that improvement in function could be obtained with some specific modifications for ASTP. The system consisted of three essential parts: the furnace, a programmable electronic temperature controller that provided the desired temperatures, and a helium rapid cooldown system (fig. 21-1).

^aNASA George C. Marshall Space Flight Center.

^bWestinghouse Research Laboratories, Pittsburgh, Pa.

[†]Principal Investigator.

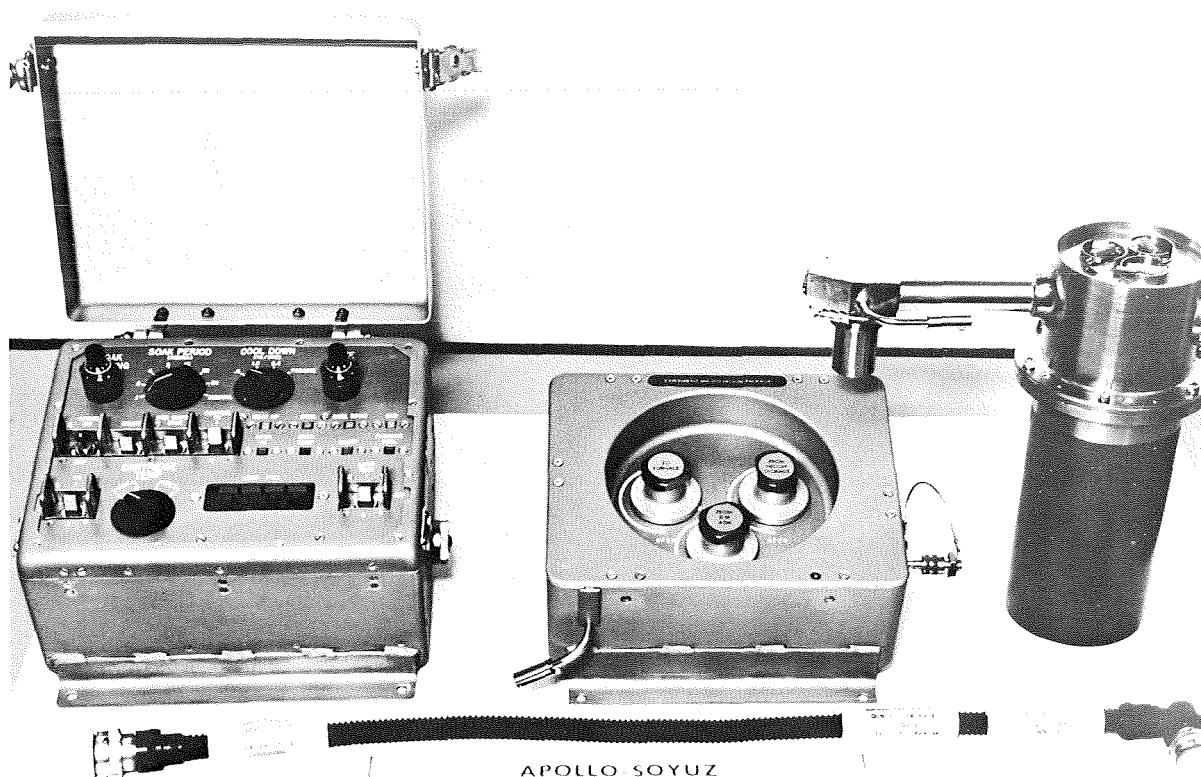


FIGURE 21-1.—Multipurpose electric furnace system.

SYSTEM DEVELOPMENT

Furnace

The design of the ASTP multipurpose furnace was prompted by two major considerations: the need for higher operating temperatures and the desire for reduced power requirements. The variety of materials experiments proposed for the ASTP mission required temperatures in excess of the approximately 1273-K (1000° C) limit of the Skylab system. Furthermore, the reduced heat dissipation capability of the ASTP vehicles dictated that these higher temperatures be obtained with no increase in power requirements (205 W).

Experience with the Skylab furnace facility indicated that somewhat higher temperature operation would be possible without any modification; however, the power requirements would be excessive. Therefore, the initial effort of the

redesign was to reduce the intrinsic heat loss. The predicted performance of the redesigned system was sufficiently encouraging that even higher temperature operation appeared feasible if it were compatible with the furnace materials, especially the heating elements. Accordingly, the high-temperature components of the furnace were carefully evaluated and, where necessary, materials were changed or assembly techniques modified to provide reliable operation.

Analysis of the Skylab furnace indicated that one significant source of heat loss was the "piping" of radiation between the heat shields. This loss could be reduced by providing a "mitered" closure of the radiation shields at both the cold and hot ends of the furnace. This type of construction would, in essence, provide a "nested can" shield configuration in which radiation leaks would occur only through the necessary clearance gaps in the shields. The efficiency of the shield

system was also increased by using two interstitial shields of 0.0127-mm (0.0005 in.) thick molybdenum foil between adjacent main shields.

Conductive heat loss through the heat leveler support tubes was also reduced. In the Skylab system, the heat leveler assembly was mechanically supported by three stainless steel (Type 310) gradient tubes that had outside diameters of 2.223 cm (0.875 in.) and walls that were 0.040 cm (0.016 in.) thick. These tubes had a combined thermal conductance of approximately 0.15 W-cm/K, which would result in a conductive loss of approximately 21 W with a furnace temperature of 1423 K (1150° C). In the modified furnace, the wall thickness of the support tubes was cut to 0.020 cm (0.008 in.), which would reduce the loss by half.

The design target maximum temperature of 1423 K (1150° C) for the heat leveler necessitated a reexamination of the heater elements. The first characteristic considered was the specific loading of the heater wires. This parameter controls the temperature difference between the wire and the workpiece; e.g., the graphite heat leveler. If the loading is too large, then the heater wire may be forced to run too hot in order to transfer the requisite power to the work. Several variations of heater design, including single and multiple ribbon heaters, were investigated. It was found, however, that the double, noninductive winding used for the Skylab furnace was nearly optimum when the additional constraint of heater resistance was imposed. The specific loading of approximately 1 W/cm² would impose a wire temperature only approximately 50 K (50° C) greater than the heat leveler temperature.

The next factor investigated was the suitability of Kanthal A-1 as heater material. Although this material is suitable for use to 1598 K (1325° C) in air, it is not recommended for use in vacuum at temperatures over 1273 K (1000° C). This warning is based on the rapid evaporation of a component from the alloy and was verified by tests performed on bare wires in ultrahigh vacuum. Sample filaments burned out after 2 hours or less at a surface temperature of 1473 K (1200° C). The heater winding, however, is not a bare wire operating in ultrahigh vacuum.

A second test was performed with a Kanthal A-1 heater wound on a salvaged Skylab heater form. In this configuration, the wire is completely surrounded by high-purity alumina. In the test facility, this heater form was filled with a graphite block to simulate the heat leveler and heavily insulated with Fiberfrax to reduce heat losses. After 144 hours of operation, the windings were still operating; however, the heater resistances had changed considerably. Examination of the disassembled unit revealed that evaporation of a volatile component had occurred and the wire was seriously degraded.

A further modification of the configuration was considered, namely embedding the heater wires in high-purity alumina cement. The life test was then repeated. The Kanthal was wound on the heater form and fired in air at 1273 K (1000° C) to form a surface oxide. A slurry of alumina powder was applied and air dried, and the heater form was then fired at 1273 K (1000° C). Finally, the test setup was reassembled. After 100 hours of operation at approximately 1473 K (1200° C), the heater resistances had changed by only 1.3 percent. Because the test time was roughly 10 times longer than the anticipated operating requirements, this design was adopted for incorporation in the prototype furnace.

Coincident with the requirement for higher temperature operation of the modified furnace, it became necessary to evaluate the higher temperature suitability of the structural materials used in the Skylab furnace design. It was immediately obvious that the only portion of the design that might be doubtful was that part of the structure in close thermal proximity to the heating element. Furthermore, it was clear that the limiting condition was that of the combined effects of graphite, alumina, and stainless steel as they exist at higher temperature in the multipurpose furnace atmosphere and pressure environment. In the Skylab furnace design, these materials are in direct physical contact.

To evaluate the limiting of this materials combination, a series of compatibility tests was carried out under conditions that approximated the multipurpose furnace environment. Alumina was promptly shown to be inert in these conditions at

the intended temperature. The margin of safe temperature for the graphite/stainless steel combination, however, was found to be very small. The intended maximum design temperature for graphite and stainless steel is 1423 K (1150° C) in the modified design. The tests indicated that this materials combination exhibited no harmful degradation at 1498 K (1225° C) but degraded seriously at 1523 K (1250° C). Thus, a furnace overtemperature of approximately 75 K (75° C) would be allowable insofar as graphite and stainless steel reaction is a concern. Although a margin of that value is probably adequate, it was desirable to provide a better choice of materials.

As a consequence, nickel was proposed as a replacement for the stainless steel, and the graphite and nickel combination was evaluated. This combination exhibited no harmful degradation even at 1560 K (1287° C), and it was deemed unnecessary to extend the evaluation to higher temperatures. The conclusion was that the graphite-nickel-alumina combination was safe to at least 1560 K (1287° C) and that the resulting overtemperature margin of 137 K (137° C) was more than adequate. The stainless steel was thus replaced with nickel in the temperature-critical areas in the modified multipurpose furnace.

A predictable consequence of increased multipurpose furnace temperature is increasingly reduced thermocouple electrical isolation resistance. This occurrence is a natural property of the magnesia insulation in the prefabricated swaged thermocouples and has the effect of reducing the resistance between the Chromel-Alumel wires and the Inconel sheaths, which, in the Skylab furnace, were electrically grounded to the furnace structure. This effect was acceptable at the 1273 K (1000° C) maximum temperature for which the Skylab furnace was designed. Because this effect is strongly temperature dependent, however, it was unacceptable at the higher (1423 K (1150° C)) maximum furnace temperature and thus required compensating design changes.

Greatly increased thermocouple resistance to a ground was obtained by electrically insulating the Inconel sheaths from the grounded furnace structure. This was accomplished in the high-temperature region by the installation of high-

purity alumina sleeves and in the low-temperature region by Teflon sleeves. Additionally, the control thermocouple Inconel sheaths were electrically connected to the regulated 10-V supply that biases the control thermocouples. This arrangement in effect applies a guard potential to the sheaths and thus eliminates the effect of the small remaining electrical leakage which exists with the insulating sleeves. The Inconel sheaths of the four measuring thermocouples were allowed to float electrically.

Experience disclosed that the seals of the access ports for the Skylab multipurpose electric furnace were not suitable for repeated use because of the excessive force required for removal. No seal leakage was ever detected. Because rotating and reciprocating seals are used routinely in high-vacuum systems, it appeared very likely that the problem with the Skylab furnace was not a fault of design principle but was rather a fault of design detail dimensions. A new design was developed.

The Skylab furnace was evacuated by evacuating the chamber in which it was situated. The ASTP furnace was evacuated through a pump line leading from the furnace through the docking module wall to space. The furnace vacuum connection was redesigned to allow for this change. The Skylab fitting was replaced by a 2.54-cm (1 in.) diameter elbow that terminated in a welded connection to the docking module pump line.

Helium Package

The Skylab multipurpose furnace was evacuated during the entire time period required for each experiment. The modified furnace, if evacuated, required as much as 20 hours of passive cooling to reach the allowed touch temperature. For the ASTP mission, cooldown periods of such duration would seriously limit the number of experiments that could be fitted into the permitted time frame. To minimize this problem, a helium rapid cooldown system was developed. With this system, the time required for cooldown was reduced to as little as 3 hours.

Rapid cooling may be provided through selective control of the heat loss of the furnace. For

minimum thermal transfer, the heat shields require a high-vacuum environment, but the thermal transfer will be greatly increased if the vacuum environment is replaced by helium. Fortunately, only a very small amount of helium is required for this purpose; approximately 1.01 kN/m^2 (0.01 atm) approaches the maximum effectiveness. For the multipurpose furnace, the volume required to produce 1004.13 kN/m^2 (9.91 atm) is approximately 0.16 cm^3 of helium at standard conditions. Within the 1.01-kN/m^2 (0.01 atm) range, the thermal transfer is weakly dependent on pressure, and it is consequently not necessary to provide a precise volumetric measure for each dosage. The helium package was designed so that successive doses of helium would be provided at slightly reduced volume.

A schematic representation of the helium package is shown in figure 21-2. During each experiment before rapid cooldown, all helium package valves must be closed. Immediately before operation of the package, the docking module valve in the overboard vacuum line to the furnace must be closed. To initiate rapid cooldown, two valve operations are required: (1) valve B must be opened momentarily to pressurize the helium dosage cavity from the helium storage tube, and (2) valve A must be opened momentarily to release the helium dosage into the

furnace. No further valve manipulation is required during the rapid cooldown period.

When cooldown is completed and the allowed touch temperature has been reached, the experiment cycle is completed. Before the furnace is opened, it should be pressurized to the same value as the docking module. This is accomplished with the helium package by momentarily opening valves A and C simultaneously and thus allowing the docking module atmosphere to flow into the furnace until the pressure is equilibrated.

Control Package

The control package for the multipurpose electric furnace system (fig. 21-3) was modified to meet a new set of requirements for the ASTP mission. These modifications included several changes of the system operating functions; mechanical modifications were also made to meet new interface requirements. A listing of these modifications and a brief description of each is presented in the following paragraphs. In addition to these items, a number of minor electronic component changes were made to provide additional safety margins in circuitry operation.

Increase in maximum control temperature.—To facilitate higher temperature experiments, the gain of the control thermocouple amplifier was altered to permit a maximum controlled heat leveler temperature in excess of 1423 K (1150° C).

Variable controlled cooldown rate.—To provide more constant solidification velocities in the experiments, circuitry was incorporated to decrease the cooldown rate continuously during the controlled cooldown portion of the experiment. A control was provided to enable selection of the amount of cooldown rate variation.

Shorted control thermocouple protection.—To protect the furnace from overheating should the control thermocouple become shorted, an additional shutdown circuit was incorporated in the control package. This circuit continuously monitors both HOT-1 and HOT-2 measuring thermocouples and automatically shuts off the furnace heaters if either of these thermocouples exceeds a preset limit temperature (nominally set at 1463 K (1190° C)).

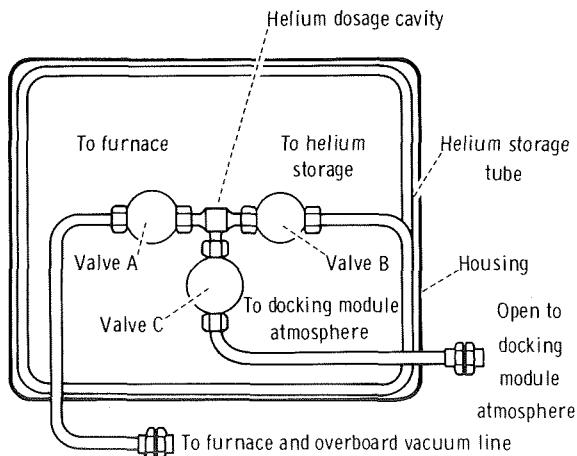


FIGURE 21-2.—Schematic representation of the helium rapid cooldown system.

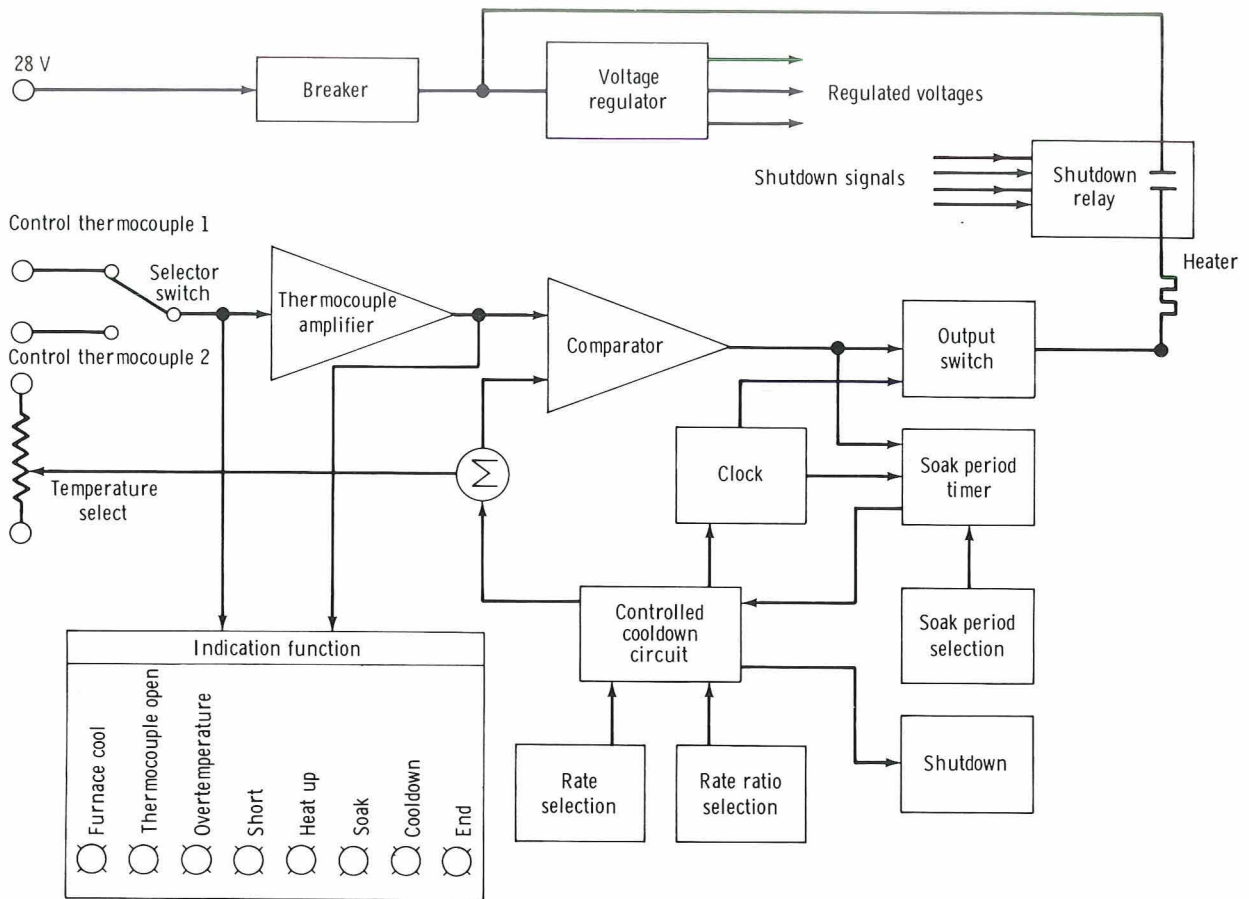


FIGURE 21-3.—Schematic representation of the furnace control system.

Mechanical interface modifications.—A new mounting mechanism and a new control cable between the control package and the furnace were designed to facilitate the ASTP system configuration. The input power and telemetry cable was provided by the vehicle integration contractor.

The operation of the ASTP control package is very similar to the operation of the Skylab control package described previously.

SUMMARY

The entire multipurpose electric furnace system performed perfectly, as had been predicted

from the ground-based testing, with one minor exception. The rapid cooldown helium system did not respond during the first experiment. It could not be ascertained whether this was a facility or an operational problem, but the system performed nominally on all subsequent experiments. Table 21-I describes the thermal cycles for the flight experiments and shows how they compare with the ground-based tests. The soak temperatures were well within the tolerances requested by the Principal Investigators.

Temperature profiles of the multipurpose electric furnace are shown in figures 21-4 to 21-10 for the seven ASTP experiments discussed in the following sections.

TABLE 21-I.—Experiment Thermal Cycles

Experiment	Heat-up time, hr: min		Soak temperature, K (°C)		Cooldown
	Ground test	Flight	Ground test	Flight	
MA-041	1:10	1:37	962 (689)	965 (692)	Extended
MA-044	2:45	3:15	1428 (1155)	1422 (1149)	Normal
MA-060	3:15	3:45	1393 (1120)	1396 (1123)	Normal
MA-070	2:30	3:07	1348 (1075)	1354 (1081)	Normal
MA-085	1:12	1:15	898 (625)	898 (625)	Normal
MA-131	2:10	2:23	1293 (1020)	1293 (1020)	Normal
MA-150	3:12	2:52	1338 (1065)	1339 (1066)	Normal

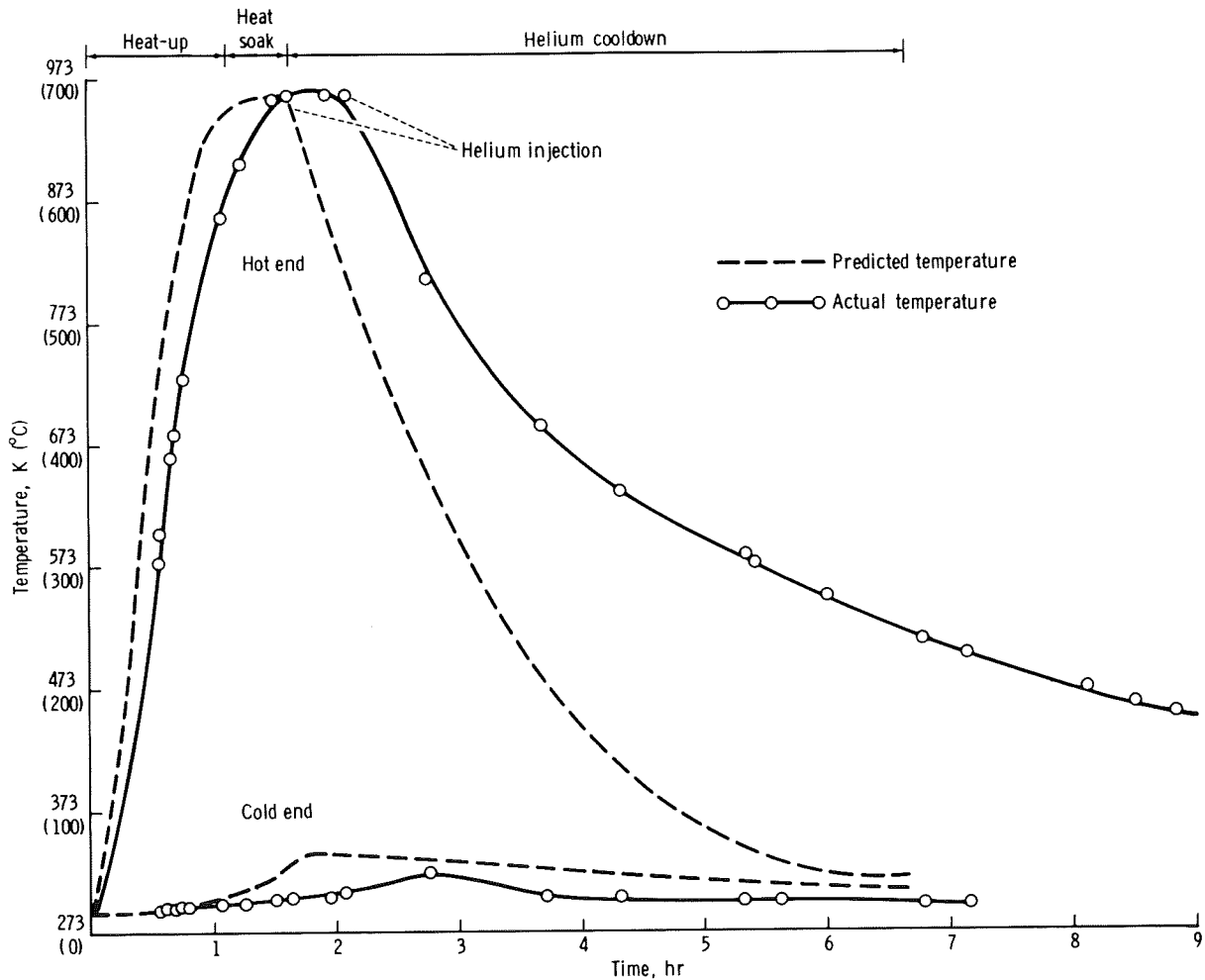


FIGURE 21-4.—Temperature profile for Surface-Tension-Induced Convection (MA-041).

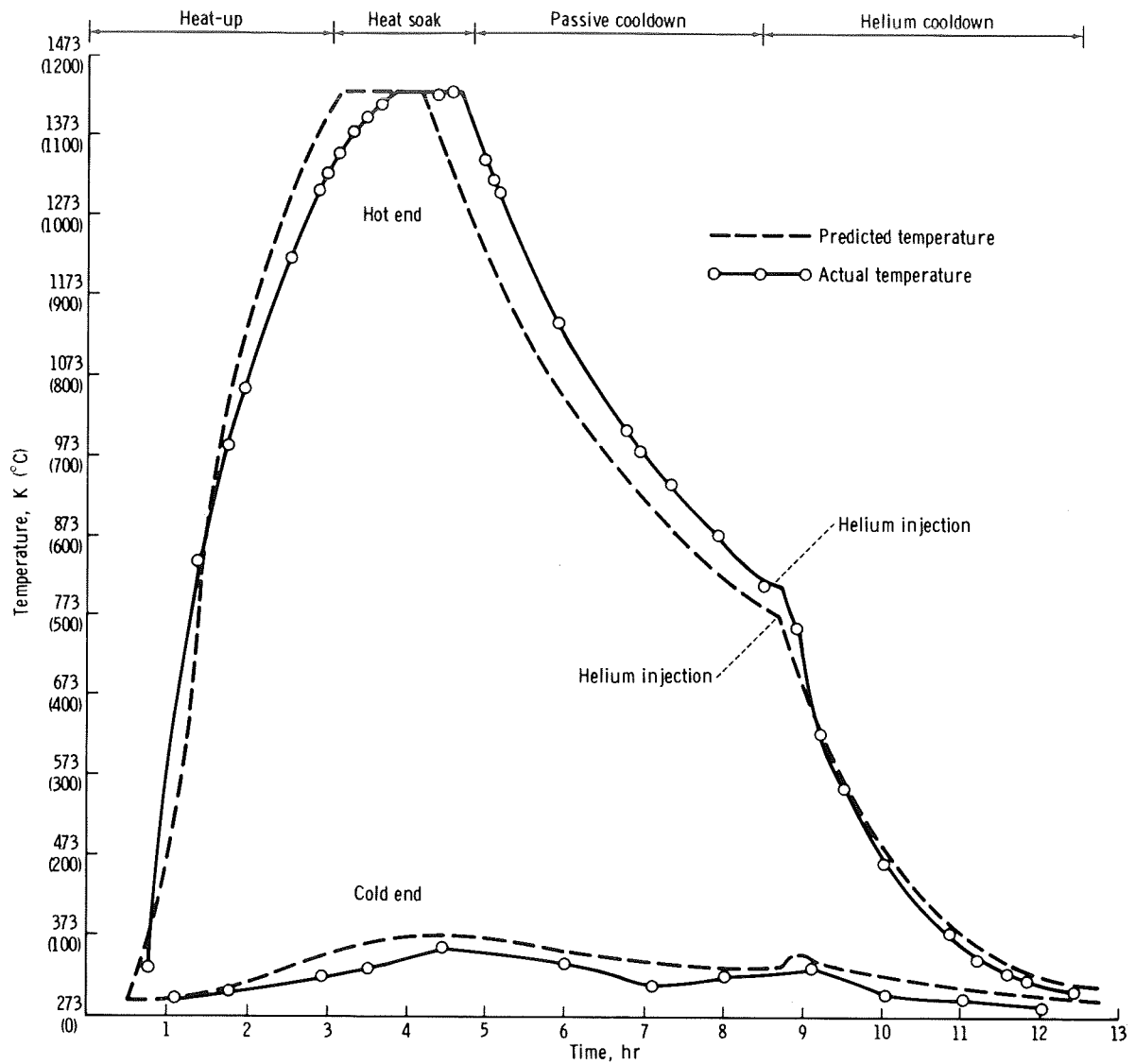


FIGURE 21-5.—Temperature profile for Monotectic and Syntectic Alloys (MA-044).

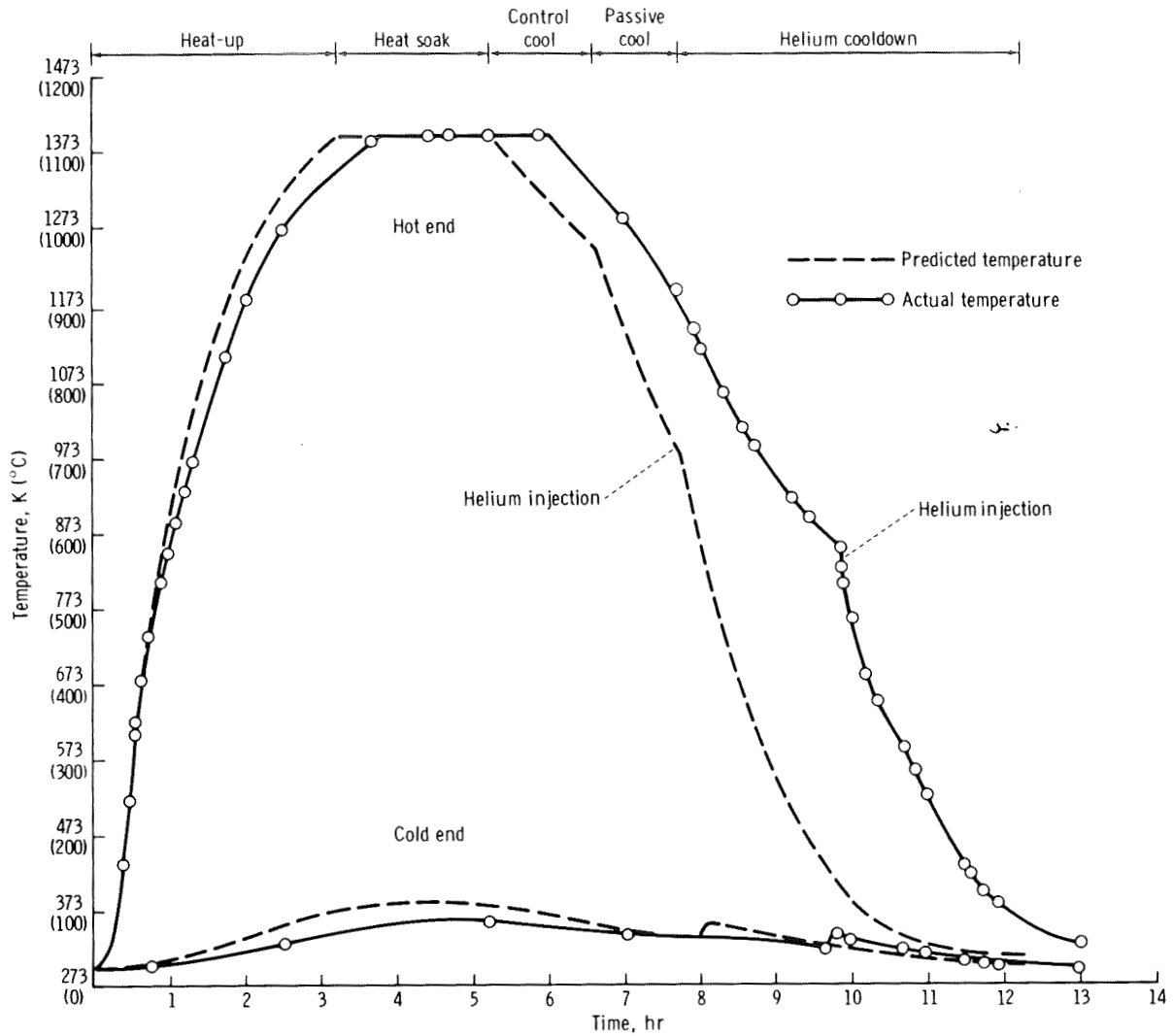


FIGURE 21-6.—Temperature profile for Interface Markings in Crystals (MA-060).

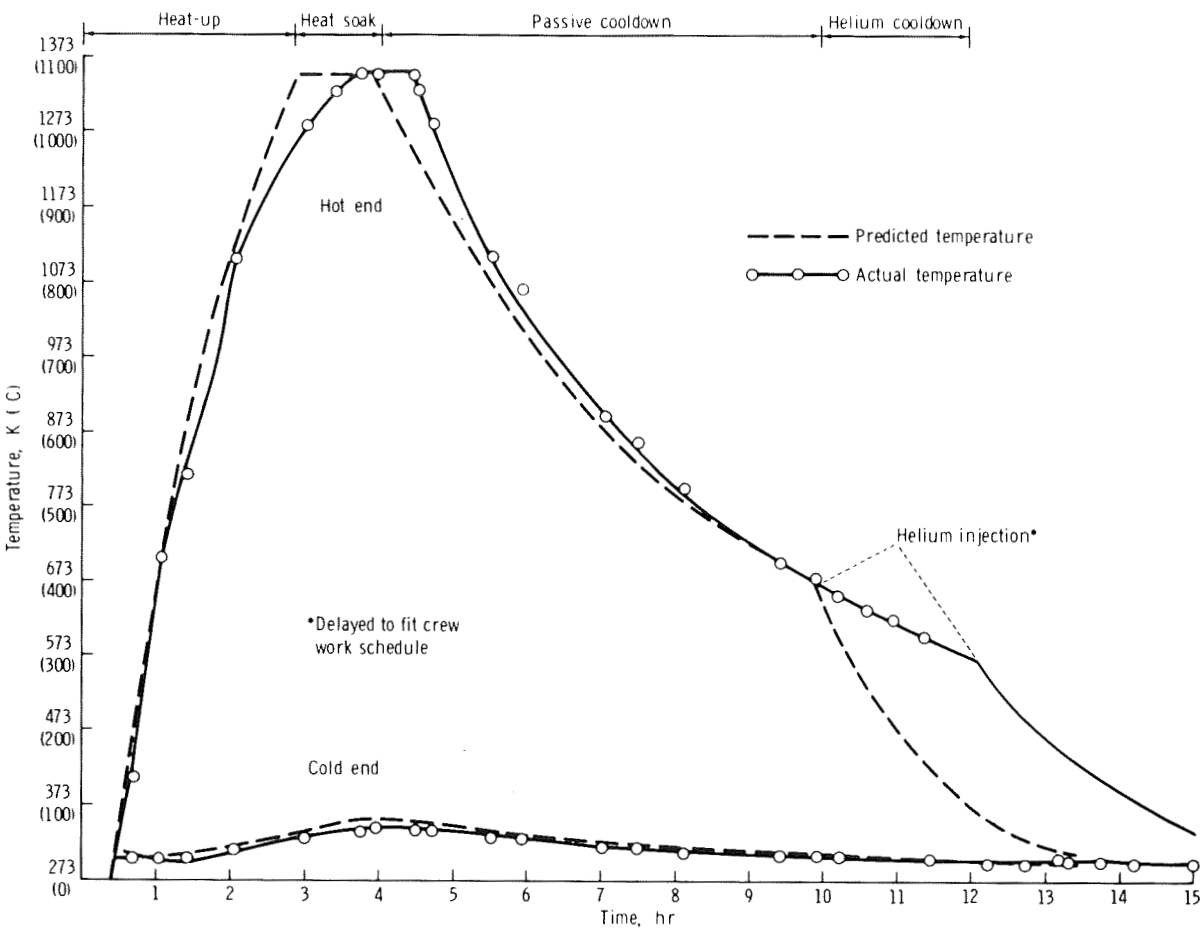


FIGURE 21-7.—Temperature profile for Zero-g Processing of Magnets (MA-070).

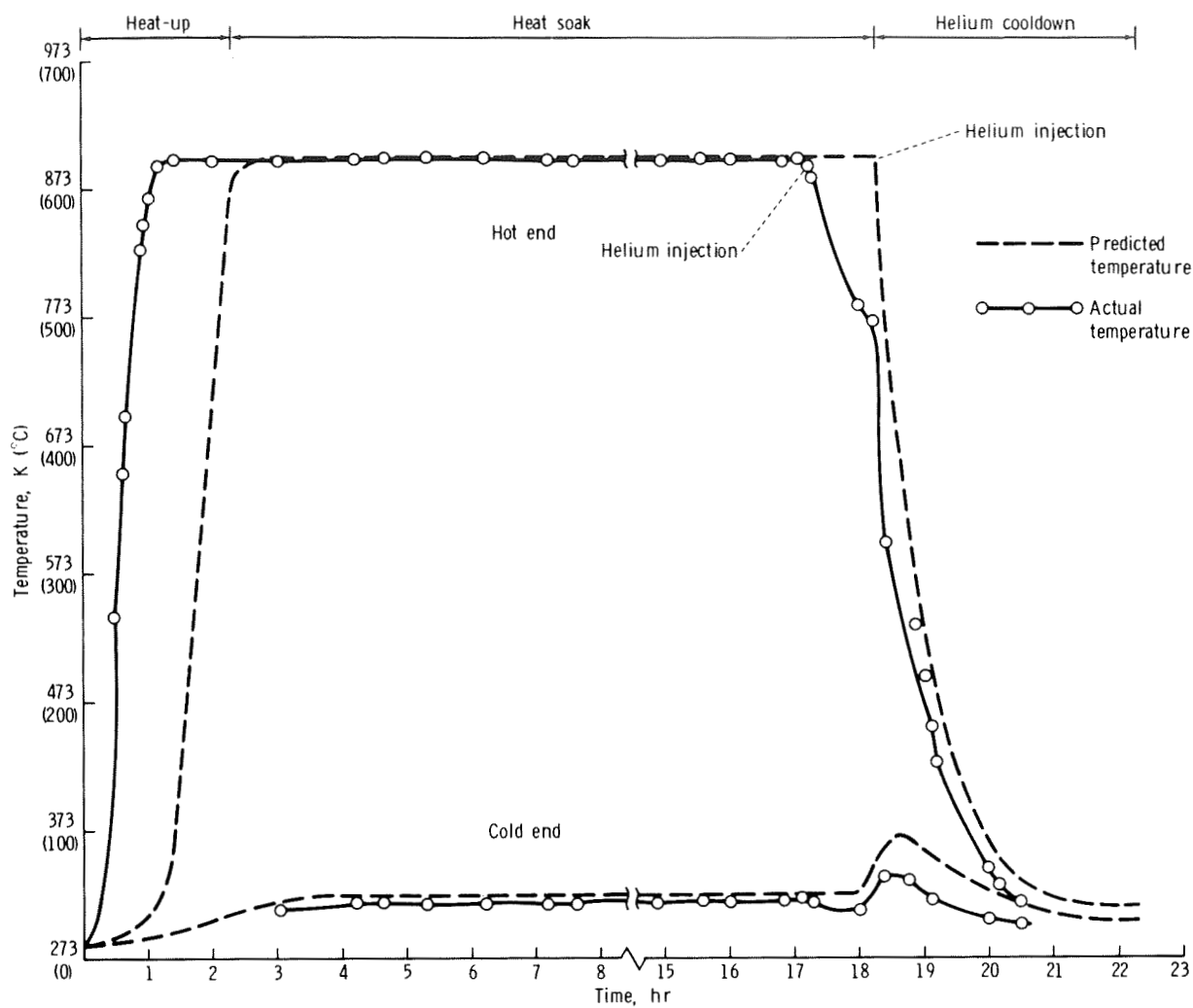


FIGURE 21-8.—Temperature profile for Crystal Growth From the Vapor Phase (MA-085).

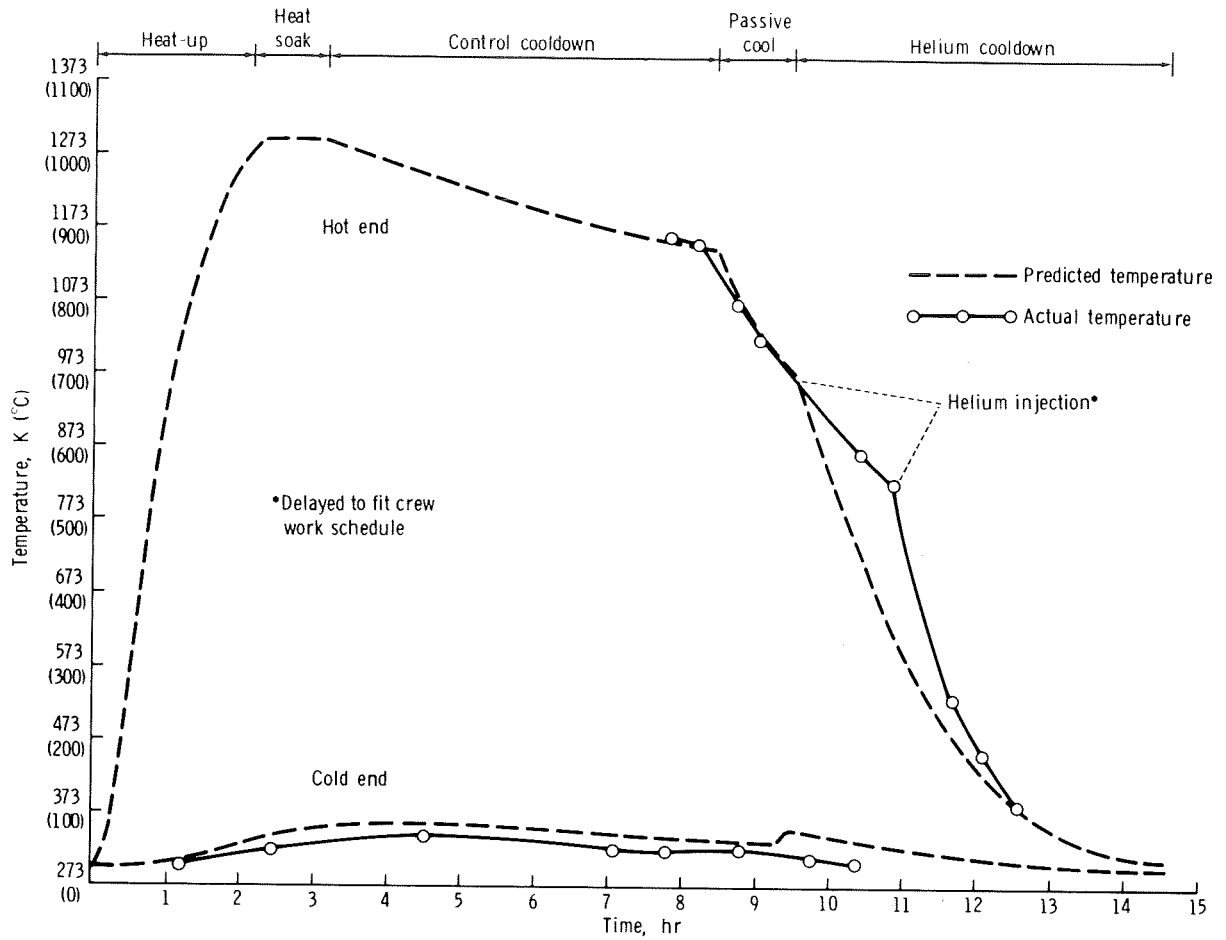


FIGURE 21-9.—Temperature profile for Halide Eutectic Growth (MA-131).

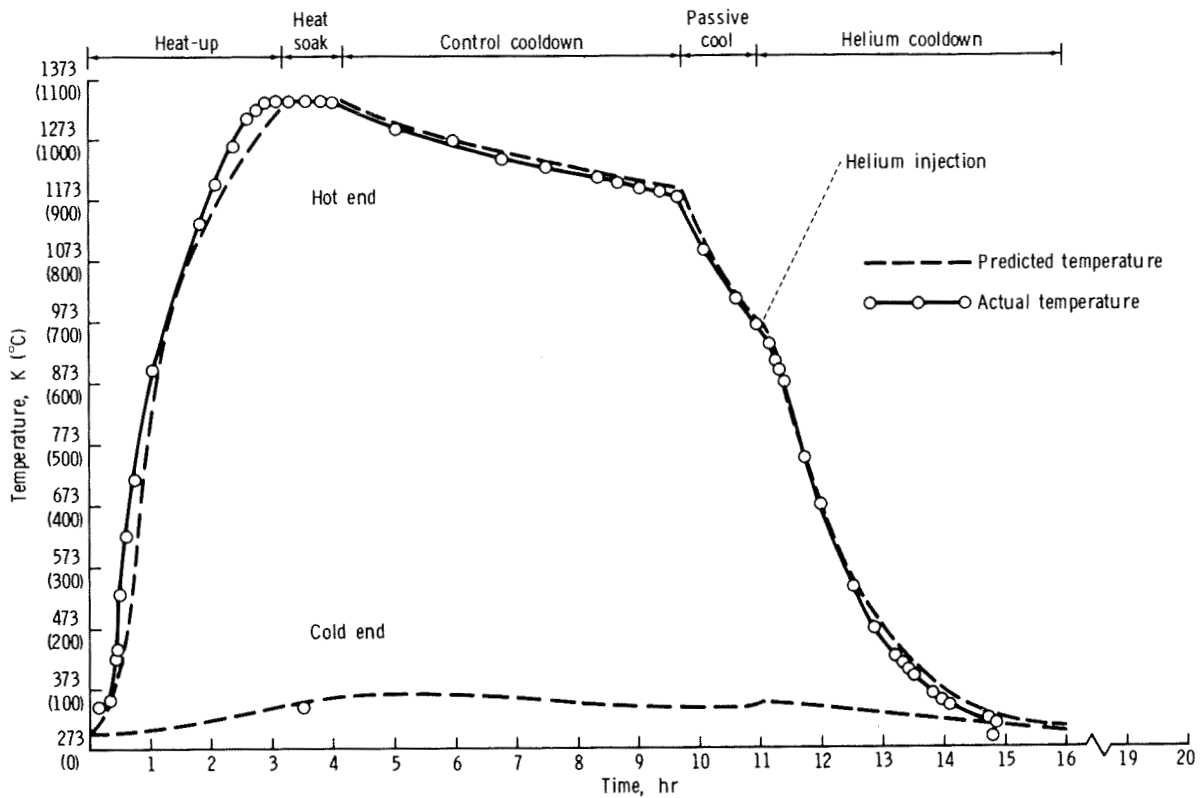


FIGURE 21-10.—Temperature profile for Multiple Materials Melting (MA-150).